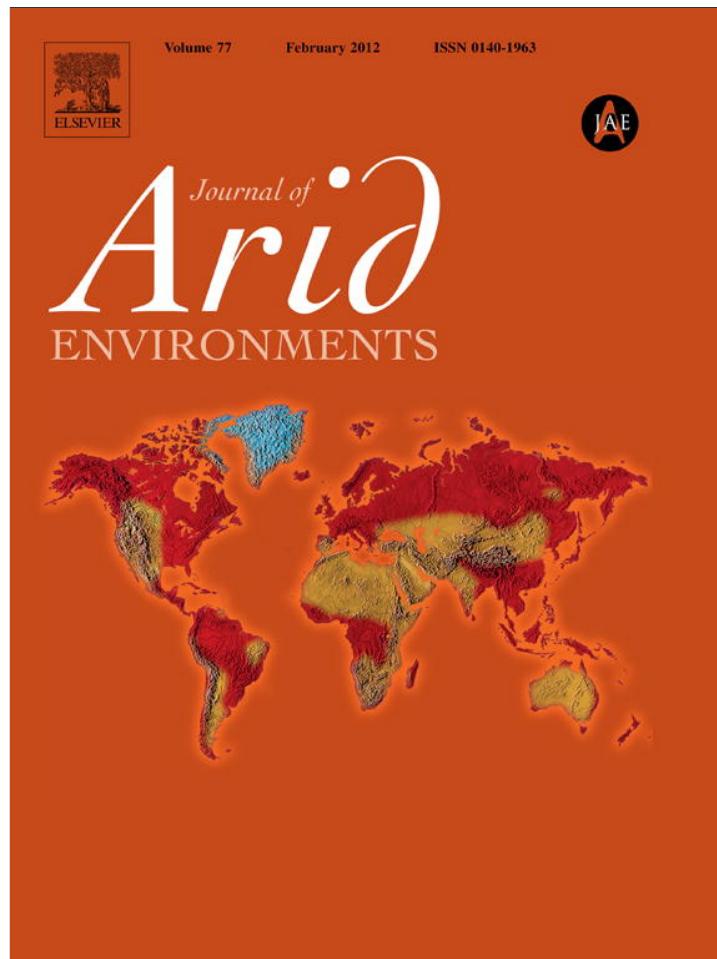


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## Evaluation of NDVI to assess avian abundance and richness along the upper San Pedro River

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## ABSTRACT

Remote-sensing models have become increasingly popular for identifying, characterizing, monitoring, and predicting avian habitat but have largely focused on single bird species. The Normalized Difference Vegetation Index (NDVI) has been shown to positively correlate with avian abundance and richness and has been successfully applied to southwestern riparian systems which are uniquely composed of narrow bands of vegetation in an otherwise dry landscape. Desert riparian ecosystems are important breeding and stopover sites for many bird species but have been degraded due to altered hydrology and land management practices. Here we investigated the use of NDVI, coupled with vegetation, to model the avian community structure along the San Pedro River, Arizona. We also investigated how vegetation and physical features measured locally compared to those data that can be gathered through remote-sensing. We found that NDVI has statistically significant relationships with both avian abundance and species richness, although is better applied at the individual species level. However, the amount of variation explained by even our best models was quite low, suggesting that NDVI habitat models may not presently be an accurate tool for extensive modeling of avian communities. We suggest additional studies in other watersheds to increase our understanding of these bird/NDVI relationships.

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### 1. Introduction

Understanding community structure and function is important for conservation of rare habitats and species that depend upon those ecosystems (Colwell and Dodd, 1995; Debinski and Brussard, 1994; Wiens and Rotenberry, 1985). Avian communities are often utilized to indicate ecosystem health (Furness et al., 1993; Morrison, 1986; Steele et al., 1984). In particular, understanding the relationship between avian habitat distribution and habitat use is imperative for implementation of successful land management actions.

Riparian woodlands in desert environments constitute a small percentage of the landscape, yet support a high diversity and density of avian species (Johnson and Haight, 1987; Knopf et al., 1988). Desert riparian systems are crucial to many avian species as migratory stopover sites (Carlisle et al., 2009; McGrath et al., 2009; Skagen et al., 1998; Yong and Finch, 2002) and as breeding

habitat (DeSante and George, 1994; Strong and Bock, 1990). However, a large portion of Southwestern riparian areas have been degraded due to agriculture, overgrazing, altered hydrologic regimes, and invasive species (Cleverly et al., 1997; Knopf et al., 1988; Robinson, 1965; Shafrroth et al., 2002; Sogge et al., 2008; Stromberg et al., 2007; van Riper et al., 2008). Loss of much of the Southwest's riparian areas are correlated with the decline in many species dependent upon desert riparian systems for one or more parts of their annual cycle (DeSante and George, 1994; Knopf et al., 1988; Rea, 1983; Strong and Bock, 1990; Skagen et al., 1998; Webb et al., 2007; Yong and Finch, 2002). Impacted bird species include, but are not limited to Bell's Vireo (BEVI; *Vireo bellii*), Lucy's Warbler (LUWA; *Vermivora luciae*), and Abert's Towhee (ABTO; *Pipilo aberti*), all which were listed in 2007 on the Arizona Audubon Watch List (see also Hunter et al., 1987). Additionally, the riparian areas of the desert southwest are important habitat to the endangered Southwestern willow flycatcher (*Empidonax traillii extimus*; USFWS, 1995) and the western subspecies of the yellow-billed cuckoo (*Coccyzus americanus occidentalis*), which is a candidate for endangered species status (Gaines and Laymon, 1984; Hughes, 1999; Hunter et al., 1987; Johnson et al., 2010; Laymon and Halterman, 1987; USFWS, 2000).

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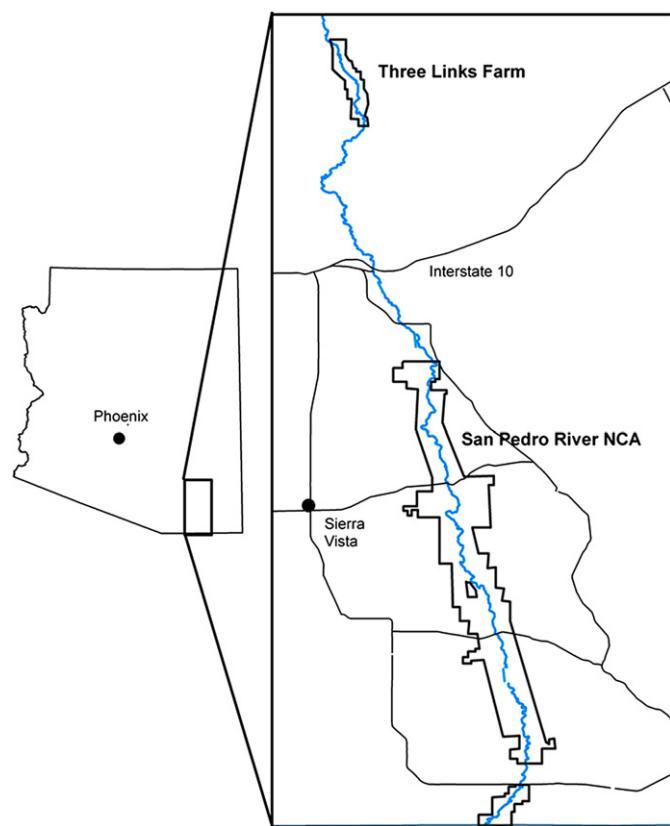
A key first step in understanding avian habitat use is to identify habitat availability and species use patterns. However, traditional on-the-ground monitoring techniques for surveying birds and documenting use patterns are expensive, time intensive and limited in scope (Ralph et al., 1995). Since 1972, when remotely-sensed imagery became widely available to the public, biologists have been investigating the use of satellite imagery to identify, characterize, monitor, and predict avian habitats over broad landscapes (Gottschalk et al., 2005), allowing for a faster and more effective development of management strategies. Gottschalk et al. (2005) summarized 109 remote-sensing studies of avian habitat conducted since 1974 (see also Gibson et al., 2004; Mathieu et al., 2006; Newbold and Eadie, 2004) and found that the majority of these satellite imagery habitat models focus on single species. The applicability of remote-sensing models to understanding broader community structure and function remains largely untested.

The Normalized Difference Vegetation Index (NDVI; Jordan, 1969; Nixon et al., 1985; Tucker et al., 1985) is a popular metric for habitat modeling (Gottschalk et al., 2005). In some instances, NDVI has been shown to correlate with avian abundance and species richness (Foody, 2005; Lee et al., 2004; Maurer, 1994; Osborne et al., 2001; Seto et al., 2004). NDVI is sensitive to photosynthetic compounds (Jordan, 1969; Nixon et al., 1985; Tucker, 1979; Tucker et al., 1985), and higher values correspond to higher amounts of photosynthetic activity, thus thicker or greener vegetation (Tucker et al., 1985). This then would suggest that NDVI would have application in desert riparian systems which are composed of narrow bands of dense green vegetation surrounded by an otherwise brown desert environment. Additionally, NDVI is a major component of the Southwestern willow flycatcher (WIFL) model which successfully predicts breeding sites of this endangered bird (Dockens et al., 2004; Hatten and Paradzick, 2003; Hatten and Sogge, 2007).

Here we investigate if NDVI can be used to create predictive models for avian abundance and species richness in riparian areas of the desert southwest. We sought to answer two questions: 1) what relationship, if any, does NDVI show with avian abundance and richness, and 2) what types of variables, those measured on the ground, those measured remotely, or a combination of both, produce better predictive models? We investigated the use of NDVI at a 30 m<sup>2</sup> pixel resolution, as well as NDVI averaged over larger areas to simulate larger pixels. Foody (2005) demonstrated that NDVI applied to even coarse-resolution imagery correlated with species richness. NDVI can be easily calculated from satellite imagery and would provide a quick means of assessing potential areas to focus management or protection efforts on. If NDVI and other remotely sensed variables (e.g., elevation, slope) can be used in place of intensively collected vegetation data to quickly predict areas of high bird abundance and richness, on-the-ground surveys would be necessary only to verify model output.

### 1.1. Study area

Our study focused on the riparian community along 45 miles of the upper San Pedro River in southeastern Arizona, within the boundaries of the San Pedro Riparian National Conservation Area (SPRNCA), land managed by the Bureau of Land Management (BLM). We sampled an additional six miles of river in 2008 on The Nature Conservancy land at Three Links Farm, approximately 15 miles north of I-10 (Fig. 1). The riparian area of the San Pedro River and the surrounding basin have extremely high biodiversity, providing breeding habitat for 389 bird species, 84 species of mammal, and 47 species of reptile and amphibian, including several endangered species (Steinitz et al., 2003). The San Pedro River is the last free-flowing river in the American Southwest.



**Fig. 1.** Map of our study site along the San Pedro river in southern Arizona, U.S.A. The San Pedro Riparian National Conservation Area is managed by the Bureau of Land Management, while Three Links Farm is managed by The Nature Conservancy.

Characterized by shallow groundwater and intermittent stream flows, this area is therefore extremely susceptible to disturbance. Population growth in the area has increased impacts to the watershed, including lowering the level of the aquifer supplying the river (Steinitz et al., 2003; Stromberg and Tellman, 2009).

## 2. Methods

### 2.1. Bird sampling

We sampled birds on the upper San Pedro River from late May through late July during three years: 2005, 2006, and 2008, using standardized point count survey methods (modified from Ralph et al., 1995). We selected a random start location and placed stations every 250 m along the river. Stations were placed approximately halfway into the riparian vegetation on a randomly chosen side of the river. In other words, if the band of riparian vegetation (i.e., predominantly cottonwood/willow) was wide, point count stations would be a further perpendicular distance from the river bed than if the segment of river had a narrow riparian corridor. We surveyed these same 242 stations in 2005 and 2006. In 2008, from a new random start point we again placed 265 new points 250 m apart along the river. The locations of the original stations had no influence over the placement of 2008 stations.

We conducted point count surveys starting 10 min after sunrise and lasting until 09:00 h. Trained observers approached survey stations quietly, waited approximately 1 min for birds to acclimate, and then recorded all birds detected for 5 min. For every bird detected, we recorded the species, detection type (aural or visual),

and distance to the bird with a laser range-finder. We monitored all stations twice in each year. After all points were visited once, we began revisiting points so that replicates occurred evenly spaced throughout the breeding season and the same number of counts occurred in the first and second halves of each season.

## 2.2. Vegetation survey

At each point count location in 2008, a vegetation survey was conducted within approximately a 30 m<sup>2</sup> area to correspond with the 30-m<sup>2</sup> pixels of the Landsat Thematic Mapper (TM) imagery. We focused our efforts on four woody tree species: Fremont Cottonwood (*Populus fremontii*), Gooding's Willow (*Salix gooddingii*), Tamarisk (*Tamarix* sp.), and Honey Mesquite (*Prosopis glandulosa*). While cottonwood, willow, and tamarisk are associated strictly with the riparian area, mesquite grows mostly in the upland areas directly adjacent to the riparian corridor, the "mesquite bosque," although it also grows in small quantities within the riparian vegetation. To estimate total canopy cover and amount composed of each species, we used a convex densiometer and took measurements at 3 m from the point count station in the four cardinal directions, always facing away from the point. We estimated the canopy cover at two height strata, between five and 15 m and above 15 m. To account for the amount of low vegetation not captured in the densiometers, we estimated the amount of vegetative cover under 5 m tall within four 5-m radius plots. In order to center these plots approximately under the densiometer readings, we noted that the densitometers reflect the vegetation above and in front of the person taking the reading. A trial run in the field determined that plots should be placed approximately 8 m away from the point count station in all four cardinal directions to compensate for the parallax of the densiometer reading. Within these four plots, we approximated the percent (to the nearest 20%) of the area covered by low woody vegetation and counted stems. We also recorded whether water was present in the river adjacent to each of our point count locations.

We designed a single calculated metric for each of the four principal tree species in order to standardize and approximate the total amount of cover that would be visible from the air at each of the four plot locations of each point count station:

$$\text{Tree Species A} = (>5\text{m}) + (\% \text{ open} * \% \text{ cover} \leq 5\text{m} * \% \text{ stems}) \quad (1)$$

where:

- >5 m = total % of plot covered by Tree Species A as measured by densiometer (>5 m)
- % open = total % of plot open to sky as measured by densiometer (>5 m)
- % cover ≤ 5 m = total % of plot covered under 5 m (visual estimate to nearest 20%)
- % stems = % stems of Tree Species A of total number of woody stems.

For each point, we averaged these outputs (Eq. (1)) across each of the four plot locations to derive an average measurement of percent cover of each tree species at each point, approximating what would be seen from above. By summing this cover estimate for each species, across all four woody tree species at each point, we were able to calculate the total cover (Tot Cover) of the plot contributed by trees at all height strata. This yielded seven vegetation variables for each point in addition to Latitude and Elevation (hereafter "local variables"; Table 1).

## 2.3. Remote-sensing

We acquired Landsat TM 30-m resolution imagery for the San Pedro River corresponding to the years and seasons of our point counts. One terrain-corrected scene (Path: 35, Row: 38) was obtained for each year during a cloud-free day falling approximately in the middle of the field season: June 14 in 2005, June 17 in 2006, and June 6 in 2008. Using bands from the red (R) and near-infrared (NIR), a floating point raster was also generated for each scene containing values for NDVI (Tucker et al., 1985).

We determined the NDVI value for all point count locations of the corresponding year by using the Sample tool in ArcMap 9.2 (ESRI, 1999–2006). Additionally, we used the Focal Statistics tool in ArcMap to calculate the average NDVI values of the pixels within different neighborhoods around each point (0.8 ha, 4.5 ha, and 10.9 ha), replicating coarser imagery such as Aster and MODIS (USGS and Japan ASTER program 2003; ORNL DAAC, 2010). For the 2008 imagery, we also calculated the maximum (max), and standard deviations (sd) of NDVI values of the pixels within the three neighborhood sizes around each point.

We acquired a digital elevation model (DEM) of our study site to obtain the elevation of our points. We used SLOPE and FOCALSUM functions in ArcMap to determine the percent of a 41-ha neighborhood that was floodplain or flat (Floodplain; slope < 2.5; Hatten and Paradzick, 2003) for each of our point count locations. This yielded 15 remotely-sensed variables per point in addition to NDVI, including Elevation and Latitude (Table 2).

## 2.4. Statistical analyses

### 2.4.1. NDVI and larger pixels

We examined bird species richness and combined abundance of all birds in relation to NDVI, and NDVI averaged over each of the three different neighborhood sizes across all three years of our study. For our calculation of bird abundance, we averaged the total number of birds found at a point during the 5-min count period over both counts at that point within a given year. However, to

**Table 1**

A list of the nine local variables that we used to build our regression models. Cottonwood was not included due to a high correlation with Tot Cover, and Latitude was not included due to a high correlation with Elevation. All variables except for Water and Latitude were  $\log_{10}(x + 1)$  transformed to meet conditions of normality.

Parameter	Description	Correlate r
Water	Presence or absence of water in river at point count location (binomial)	
Tot Cover	Average percent of total cover (all height strata, as if viewed from above) within four quadrants of point count location	
Cover >15 m	Average value (0–5) of low vegetation within four quadrants of point count location	
Cover 5–15 m	Average percent of cover between 5 and 15 m tall within four quadrants of point count location	
Cover < 5 m	Average percent of cover under 5 m tall within four quadrants of point count location	
Mesquite	Average percent of mesquite cover at all height strata as seem from above within four quadrants of point count location	
Willow	Average percent of willow cover at all height strata as seem from above within four quadrants of point count location	
Tamarisk	Average percent of tamarisk cover at all height strata as seem from above within four quadrants of point count location	
Elevation	meters above sea level	
Cottonwood	Average percent of cottonwood cover at all height strata as seem from above within four quadrants of point count location	Tot Cover 0.830
Latitude	Northing value in grid format, NAD27 UTM Zone 12 N	Elevation –0.998

**Table 2**

A list of the eight NDVI-related remote-sensing variables that we used to build our regression models. The bottom five variables were not included due to high correlation factors with other variables.

Parameter	Description	Correlate	r
NDVI	NDVI value at point count location ( $30 \text{ m}^2$ or 0.09 ha)	NDVI	0.843
Max 0.8 ha	maximum NDVI value within a 0.8 ha neighborhood		
SD 0.8 ha	standard deviation in NDVI values within a 0.8 ha neighborhood		
Avg 10.9 ha	average NDVI value within a 10.9 ha neighborhood		
Max 10.9 ha	maximum NDVI value within a 10.9 ha neighborhood		
SD 10.9 ha	standard deviation in NDVI values within a 10.9 ha neighborhood		
Floodplain	% floodplain or flat of 41 ha neighborhood		
Elevation	meters above sea level		
Avg 0.8 ha	average NDVI value within a 0.8 ha neighborhood	NDVI	0.843
Avg 4.5 ha	average NDVI value within a 4.5 ha neighborhood	Avg 10.9 ha	0.923
Max 4.5 ha	maximum NDVI value within a 4.5 ha neighborhood	Max 10.9 ha	0.896
SD 4.5 ha	standard deviation in NDVI values within a 4.5 ha neighborhood	SD 10.9 ha	0.878
Latitude	Northing value in grid format, NAD27 UTM Zone 12 N	Elevation	-0.998

obtain the metric for richness, we used the total number of species detected across all visits of each point. We only used bird detections that were  $\leq 50 \text{ m}$  of the observer for analyses because we felt that associating birds detected within 50 m of a point with that point was still a reasonable distance to ensure birds are actively using the habitat available at the point.

Although the points in 2005 and 2006 were the same, we used them as separate yearly units due to a new NDVI value for each year. The NDVI value differed between the two years by an average of 0.065 (coefficient of variation = 0.83). We used general linear models for analyses of bird numbers relative to NDVI. To account for the effects of year, whether due to observer biases or actual differences in bird numbers or vegetation foliage among years, year was a covariate in all of our models.

Additionally, we looked at relationships between NDVI values at locations where we detected species of conservation concern (including Abert's towhees, Bell's vireos, Lucy's warblers, summer tanagers, Southwestern willow flycatchers, and yellow-billed cuckoos) and also the range of NDVI values sampled.

#### 2.4.2. Additional variables

We only measured detailed vegetation structure in 2008, so this year alone is included in our investigation into additional variables for modeling bird communities. Therefore, we used general linear models to examine the relationship between NDVI and each of our two bird-survey variables, this time using only 2008 data to compare these regression outputs to those investigating additional variables.

Due to non-normality, we transformed all local variables except Water and Latitude with a  $\text{Log}_{10}(x + 1)$  transformation. We also squared the values of Floodplain to meet conditions of normality. We looked for correlations among our local variables and among our remote-sensing variables. When two variables were highly correlated ( $r \geq 0.8$ ), we removed one of the two parameters (Tables 1 and 2).

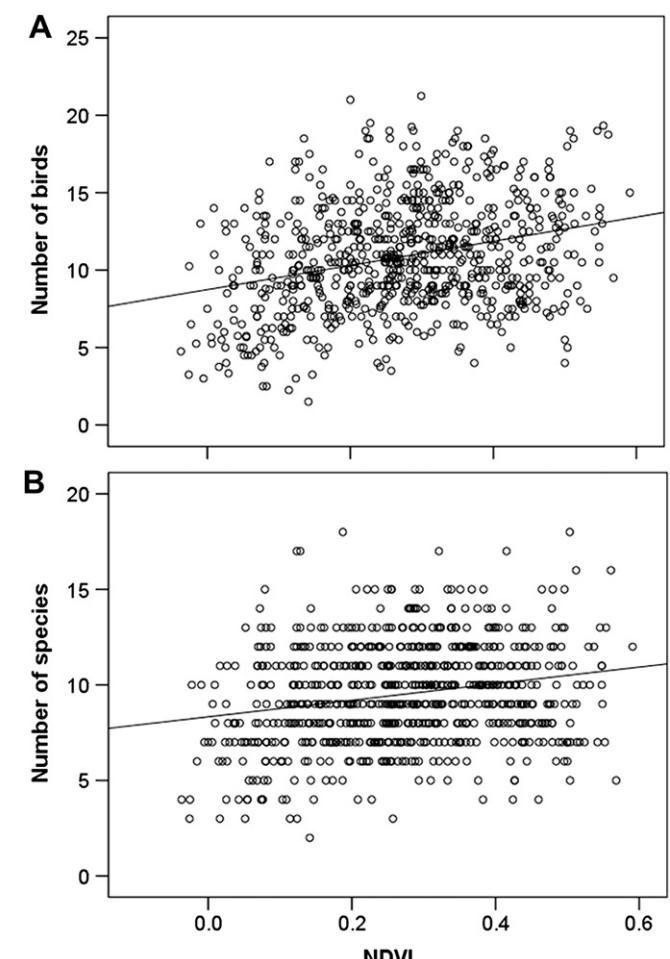
A forward stepwise linear regression was used to select our models. We first determined what local variables most influence NDVI, then ran stepwise regressions separately for abundance and richness with each set of variables: local variables, remotely-sensed variables, and all variables together. Latitude and Elevation were included as both local and remotely-sensed variables (Tables 1 and 2), since both can be determined on the ground with a GPS unit or

by remote-sensing. Whenever Water, our only binomial parameter, was included, we used a Student's t-test to determine Water's effect on the response variable. Finally, we compared the  $R^2$  values of our resulting models for abundance and also compared the resulting models for richness to determine whether the model containing local variables, remotely-sensed variables, or all variables together explained the greatest variation.

## 3. Results

### 3.1. NDVI and larger pixels

The NDVI values at our sample points were normally distributed within each year of our surveys (2005: mean = 0.265, sd = 0.132; 2006: mean = 0.292, sd = 0.130; 2008: mean = 0.265, sd = 0.136) and across all three years of surveys (mean = 0.273, sd = 0.133). Bird abundance showed a positive relationship with NDVI after accounting for year (Fig. 2; Table 3). Species richness also increased as NDVI increased when year was accounted for (Fig. 2; Table 3). We still found positive linear relationships with bird abundance and species richness when NDVI was averaged over each of our three defined neighborhood sizes (0.8 ha, 4.5 ha and 10.9 ha), (Table 3). For both abundance and richness, the amount of explained variation slightly increased when NDVI was averaged over a 0.8 ha neighborhood but then consistently decreased as the neighborhoods increased in size.



**Fig. 2.** Regression lines between bird abundance (A) or bird species richness (B) and NDVI at the point ( $30 \text{ m}^2$ ) for all three years, after accounting for year and an interaction term. NDVI was found to have a positive relationship with both bird parameters.

**Table 3**

Results of linear regressions between bird abundance or species richness and NDVI at a 30 m<sup>2</sup> pixel or NDVI averaged over increasingly large neighborhood sizes (0.8 ha, 4.5 ha, and 10.9 ha). Even at the largest neighborhood size, both abundance and richness showed a positive relationship with NDVI.

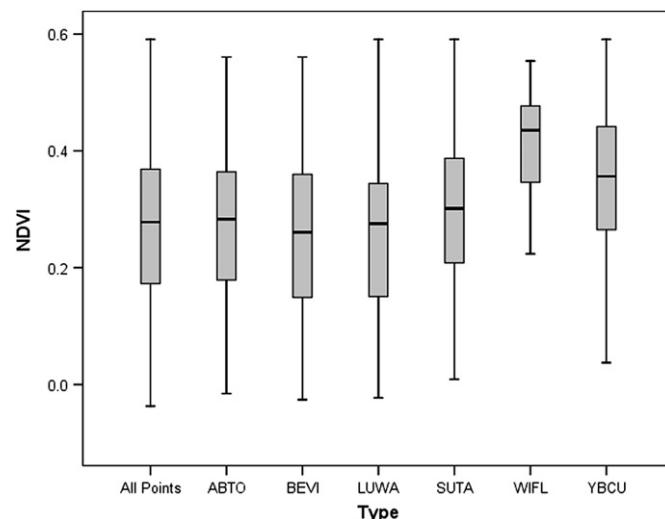
	R <sup>2</sup>	NDVI		Year		NDVI * Year	
		F <sub>1,733</sub>	p	F <sub>2,733</sub>	p	F <sub>2,733</sub>	p
<b>Abundance</b>							
30 m <sup>2</sup>	0.295	106.475	*	96.337	*	8.399	0.0002
0.8 ha	0.329	147.592	*	97.085	*	9.914	*
4.5 ha	0.271	77.743	*	80.537	*	9.218	*
10.9 ha	0.218	27.752	*	75.353	*	5.839	0.003
<b>Richness</b>							
30 m <sup>2</sup>	0.185	54.56	*	49.369	*	10.414	*
0.8 ha	0.199	64.072	*	48.501	*	12.92	*
4.5 ha	0.158	26.204	*	44.357	*	11.991	*
10.9 ha	0.131	5.576	0.019	43.557	*	8.498	0.0002

\*less than 0.0001.

When we examined the range of NDVI values where our species of concern were detected, in comparison to the range of all NDVI values that were sampled, we found that willow flycatchers were detected within a narrower range of higher NDVI values (Fig. 3). The mean NDVI values of the detections of both summer tanagers and yellow-billed cuckoos were higher (0.021 and 0.078, respectively) than the mean NDVI value of all of our sample points (0.273), but the range was similar. However, we found that the NDVI values at detections of Abert's towhees, Bell's vireos, and Lucy's warblers had a similar mean and distribution to that of the entire sample (Fig. 3).

### 3.2. Additional variables

Since the San Pedro River runs south to north, Latitude and Elevation were highly correlated ( $r = -0.998$ ), so Latitude was not used in regressions using local or remotely-sensed variables (Tables 1 and 2). Cottonwood was highly correlated to Tot Cover ( $r = 0.8295$ ), so Cottonwood was removed, leaving nine total local variables (Table 1). Many of the remotely-sensed variables derived from NDVI were also correlated, leaving only eight remote-sensing variables including Elevation (Table 2).



**Fig. 3.** Distribution of NDVI values for all points surveyed on the San Pedro River across three years of study ( $N = 736$ ), of detection points for Abert's towhees (ABTO;  $N = 356$ ), Bell's vireos (BEVI;  $N = 301$ ), Lucy's warblers (LUWA;  $N = 208$ ), summer tanagers (SUTA;  $N = 317$ ), southwestern willow flycatchers (WIFL;  $N = 5$ ), and yellow-billed cuckoos (YBCU;  $N = 52$ ).

### 3.2.1. Local variables

When NDVI was modeled using our local variables, the regression selected vegetation at two height strata (Cover > 15 m, and Cover < 5 m), as well as Total Cover, Water, and Mesquite, for inclusion in the model ( $R^2 = 0.370$ ;  $F_{5,259} = 30.392$ ,  $p < 0.001$ ; Table 4). NDVI was found to be 0.063 higher (95% CI between 0.035 and 0.092) at points where water was present ( $t = 1.969$ ,  $p < 0.05$ ). However, increasing amounts of mesquite had a negative effect on NDVI (Table 4).

Bird abundance was best predicted by Water, Willow, and Mesquite (adjusted  $R^2 = 0.124$ ,  $F_{3,261} = 13.544$ ,  $p < 0.001$ , Table 4). Abundances of birds were significantly higher where water was present (1.469, 95% CI between 0.745 and 2.194,  $t = 1.969$ ,  $p < 0.05$ ). Increasing Willow had a positive effect on bird abundance, but increasing amounts of Mesquite resulted in fewer birds (Table 4).

Species richness was best predicted by Willow, Mesquite, and Elevation (adjusted  $R^2 = 0.158$ ,  $F_{3,261} = 17.528$ ,  $p < 0.001$ , Table 4). Richness increased with increasing amounts of Willow and with Elevation, but richness decreased as Mesquite increased (Table 4).

### 3.2.2. Remotely-sensed variables

The use of other remotely-sensed variables did increase the amount of explained variation over NDVI alone for avian abundance and species richness (Fig. 4). When modeled with NDVI alone, bird abundance had a positive relationship with NDVI, but considerable variation was still unaccounted for (adjusted  $R^2 = 0.085$ ,  $F_{1,263} = 25.641$ ,  $p < 0.001$ ). When we added the other remotely-derived variables (Table 2) to NDVI and ran a stepwise regression, the regression selected Max 0.8 ha, SD 0.8 ha, and Avg 10.9 ha in the model for abundance (adjusted  $R^2 = 0.147$ ,  $F_{3,261} = 16.179$ ,  $p < 0.001$ , Table 5), where increasing SD 0.8 ha and Avg 10.9 ha decreased bird abundance but increasing Max 0.8 ha increased bird abundance.

We did not find a relationship between species richness and NDVI alone in 2008 (adjusted  $R^2 = 0.006$ ,  $F_{1,263} = 2.663$ ,  $p = 0.104$ ). When we added all remote-sensing variables and ran the regression, the model selected only Elevation and Floodplain to model richness, where richness increased with an increase in both elevation and floodplain size (adjusted  $R^2 = 0.118$ ,  $F_{2,262} = 18.686$ ,  $p < 0.001$ , Table 6).

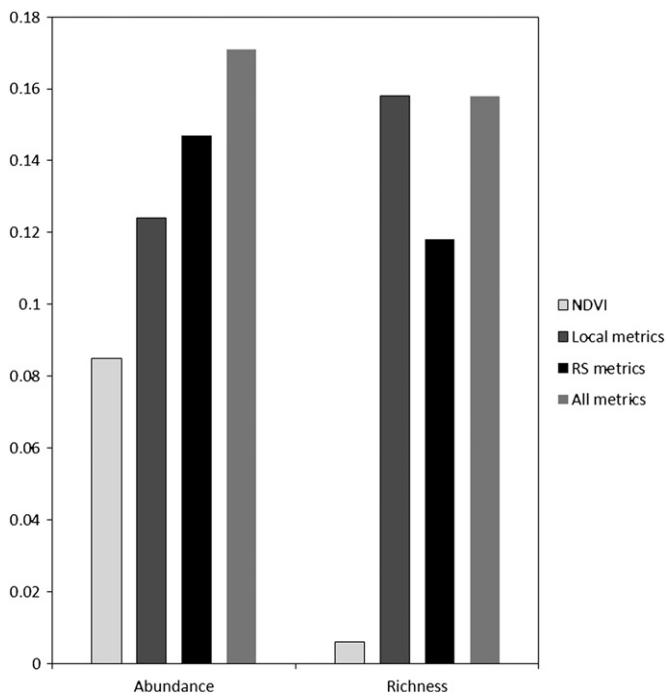
### 3.2.3. All variables

When we added all of our local and remotely-sensed variables into a stepwise model, model selection determined abundance to be best modeled with Max 0.8 ha, Willow, Mesquite, and Water (adjusted  $R^2 = 0.171$ ,  $F_{4,260} = 14.610$ ,  $p < 0.001$ ). However, when we ran the same regression for species richness, we obtained similar

**Table 4**

NDVI, abundance, and richness modeled by vegetation. Variables were selected by stepwise regression analysis. Sample size was 265 for all regressions.

	Term	Estimate	Std Error	t ratio	Prob> t
NDVI	Intercept	-0.068	0.039	-1.755	0.081
	Water	0.063	0.015	4.361	<0.001
	Tot Cover	0.058	0.020	2.906	0.004
	Cover > 15 m	0.046	0.016	2.916	0.004
	Cover < 5 m	0.129	0.025	5.189	<0.001
	Mesquite	-0.110	0.037	-3.017	0.003
	Intercept	11.697	0.312	37.477	<0.001
Abundance	Water	1.469	0.368	3.996	<0.001
	Willow	1.301	0.372	3.497	0.001
	Mesquite	-2.446	0.956	-2.558	0.011
	Intercept	-0.836	2.045	-0.409	0.683
Richness	Willow	1.043	0.319	3.267	0.001
	Mesquite	-2.467	0.825	-2.989	0.003
	Elevation	0.011	0.002	6.127	<0.001



**Fig. 4.** Differences in explained variation ( $R^2$ ) among models for avian abundance and species richness using NDVI, including vegetation and remotely-sensed data from the San Pedro River in southern Arizona, U.S.A. Avian Species Richness is best modeled with vegetation alone, while bird abundance is best modeled with a combination of remotely-sensed and vegetation variables. When given all possible variables, a stepwise regression for bird richness yielded the same results as the vegetation only model.

results as when the regression was run with the local variables only (Willow, Mesquite, and Elevation, Table 4).

### 3.3. Model comparison

Comparing all the regression models based on the amount of variation they explain, the most variation is explained for abundance models that include remotely-sensed variables, with and without local variables (Fig. 4). For richness, local variables alone explained the most variation, and no remote-sensing variables were chosen when all variables were provided. However, even the best models for both abundance and richness explained only about 17% of the variation.

## 4. Discussion

Our data suggest that utilizing only remote-sensing variables is not suitable for modeling avian abundance and richness along the riparian area of the San Pedro River. Although the relationships that

**Table 5**

Avian abundance and richness modeled with all remotely-sensed variables. All variables were selected by stepwise regression analysis. Sample size was 265 for all regressions.

	Term	Estimate	Std Error	t Ratio	Prob> t
Abundance	Intercept	10.179	0.804	12.656	<0.001
	Max 0.8 ha	16.499	2.529	6.523	<0.001
	SD 0.8 ha	-21.673	7.116	-3.045	0.003
	Avg 10.9 ha	-8.728	3.665	-2.382	0.018
Richness	Intercept	-0.386	2.075	-0.177	0.859
	Elevation	0.010	0.002	5.420	<0.001
	Floodplain	1.358	0.588	2.309	0.022

**Table 6**

Abundance modeled with all available variables. All retained variables were selected by stepwise regression analysis. Variables selected for Richness were the same as in Table 4. Sample size was 265 for all regressions.

	Term	Estimate	Std Error	t ratio	Prob> t
Abundance	Intercept	9.258	0.685	13.515	<0.001
	Max 0.8 ha	7.395	1.876	3.943	<0.001
	Willow	1.012	0.369	2.740	0.007
	Mesquite	-2.278	0.932	-2.444	0.015
	Water	0.912	0.385	2.371	0.018

we found between NDVI and avian numbers (abundance and species richness) were statistically significant, the relationships were weak. For example, when we examined only our 2008 data, the relationship between NDVI and species richness was not detectable. Moreover, the amount of variation explained by the relationships decreased as we averaged NDVI over larger areas. Even when additional variables were added, the predictive power of all models remained low.

However, NDVI has been successfully used in habitat models for riparian species in other locations in the southwest, specifically Arizona and New Mexico for the southwestern willow flycatcher (Dockens et al., 2004; Hatten and Paradick, 2003; Hatten and Sogge, 2007). When we examined the range of NDVI values for our five species of concern, only the southwestern willow flycatcher showed evidence of a preference for a narrow range of NDVI values. While southwestern willow flycatchers are known to prefer higher NDVI values (>0.41; Hatten et al., 2010), yellow-billed cuckoos also prefer more dense vegetation (Anderson and Laymon, 1988; Johnson et al., 2010). But we detected yellow-billed cuckoos only at NDVI values that were, on average, only slightly higher than all sampled points. Our data point out the difficulty of applying NDVI values as a predictor of avian community preferences over large geographic expanses, but also demonstrate the usefulness of NDVI as an indicator of habitat associations for individual species. However, we suggest additional studies in other watersheds to increase our understanding of these bird/NDVI relationships.

We found that the local variables that had the most predictive ability for NDVI were generally not the same variables that were correlated with bird abundance or richness. Since NDVI can be affected by many landscape variables such as the composition of tree species, the way the trees are grouped, the amount of understory, the soil type, phenological changes, and the presence of water (Nagler et al., 2004; Nicholson and Farrar, 1994; Prasad et al., 2008), the inclusion of such variables into our regression models allowed us to account for multiple habitat differences. Even the additions of these local variables generally did not enhance the ability of NDVI to predict avian community preferences on the San Pedro.

While the NDVI value at each avian census point was not good in predicting avian abundance or species richness, the maximum NDVI value within a 0.8 ha neighborhood was selected in our regression models as an indicator of avian abundance. This effect could well be due to birds responding to a general location that had resources located over a wider area, than just the resources present at the counting station. Therefore, one could be counting in an area with an NDVI value indicating low vegetation productivity, but detect many birds that were located in or on the edge of a region of higher productivity. Similarly, the effect of SD 0.8 ha might be a product of fewer high productivity cells due to a more heterogeneous habitat in a small area (increasing SD 0.8 ha), thus causing fewer birds to be located in the general area.

Richness was best explained by two variables, Elevation and Floodplain. Floodplain was also a metric that was an integral part of

Hatten and Paradzick's (2003) southwestern willow flycatcher model. While flat areas and resulting floodplains along a riparian area do usually correlate with dense, wetland vegetation (cottonwood/willow), floodplain size was not correlated with any of our local variables. Possibly, the low ground water level of the San Pedro River could be confounding the effect of floodplain. Thus, as the groundwater level below the San Pedro declines over time (Stromberg and Tellman, 2009), diversity of riparian plant species will certainly decline and species composition will shift from cottonwood/willow trees to more drought tolerant shrub species like tamarisk or mesquite (Stromberg et al., 2007). This would cause the large floodplains on the upper part of the San Pedro River to have less dense vegetation as happens on other southwestern rivers that are dammed or where flow is less intermittent (Hatten et al., 2010; Stromberg et al., 2007). The change would certainly mean that NDVI would become an even less powerful predictor of avian community structure and species richness as the floodplain changes.

The total amount of cover was only included in the model for NDVI and was not selected in our models for avian abundance or richness, indicating that the types of vegetative species composing the cover (and not just the amount of cover) is important to birds on the San Pedro (Strong and Bock, 1990). Certain species-specific vegetative parameters were incorporated into our regression models. Willow was selected in all models for avian abundance and richness that included local variables, and always had a positive relationship with bird numbers. Willow (*Salix* spp) has been found to be important foraging substrate for avian species (DeLay et al., 1999; Morrison et al., 1994). Mesquite was also selected in all models where local parameters were included, but consistently had a negative relationship with NDVI and our bird numbers. Since vegetation surveys encompassed approximately 15 m on each side of the point count, it is likely that areas where mesquite was detected had a narrower area of cottonwood-willow than sites without mesquite. Less riparian vegetation (a narrower riparian corridor) would thus yield a lower NDVI value, and these areas would also support fewer numbers and a lower diversity of birds.

Tamarisk was not included in any of our models. While tamarisk was present at 114 of our 265 point locations, we only had eight points where 10% or more of the cover as seen from above was composed of tamarisk. The effects of tamarisk could possibly have been lost due to a small sample size. However, willow and mesquite were also found only in small quantities at our sites, with only 40 points being 10% or more covered by willow and zero points having that much mesquite, yet the effects of these trees were still important in multiple models. Tamarisk is generally considered to have low arthropod abundance and a less diverse arthropod community compared to native vegetation (DeLay et al., 1999; DeLoach et al., 2000; McGrath et al., 2009; Yard et al., 2004), and there is still much debate over the role of tamarisk as habitat for birds (Cersale and Guglielmo, 2010; Paxton et al., 2011). Therefore, the effect of tamarisk on birds is less important than are other native plant species as has been shown on the Colorado River by van Riper et al. (2008).

Water was included in both models for avian abundance that incorporated local variables. The presence of water always increased NDVI as well as our bird variables, even though the spectral signature of water actually lowers the NDVI value in mixed pixels (Justice et al., 1985; Pettorelli et al., 2005). We can thus assume that the presence of water increases NDVI by supporting more vegetation at a site. During the dry summer in the desert, areas along the river where water is present tend to have fuller canopies and support more cottonwoods and more dense vegetation (Brand et al., 2008; Mills et al., 1991) and would thus have higher NDVI values, and in fact we did detect more birds in these areas.

The results of our adjusted  $R^2$  values suggest that NDVI and NDVI-related variables have more potential for use in modeling avian abundance, than in modeling avian species richness. But even our best models for abundance failed to explain a great deal of the variation. A large source of sampling error could have been associated with avian detection during point counts, although we minimized the effect of observer bias by training, using only a single observer, and only counting birds detected within a 50 m radius. Also, detected birds could have just been passing through, thus our avian detections were not related to the quality of the habitat (Van Horn, 1983). But we did confine our surveys to the breeding season when bird movement is minimized. Because we assessed the abundance and richness of all avian species, not all bird species were strictly affiliated with riparian vegetation and this might have artificially raised the numbers or diversity counts of areas with more upland-like vegetation (mesquite). However, we found that the exclusion of non-riparian species did not improve the predictive ability of our regression models.

While some of the variation within our models might be attributed to errors associated with remote-sensing and avian surveys, the relationships that we found between NDVI and avian abundance and richness are not robust. Even though we found that NDVI has statistically significant relationships with both avian community abundance and avian species richness, the amount of variation explained by even our best models was quite low. We thus conclude that NDVI habitat models may not presently be an accurate tool for extensive modeling of avian community structure along riparian corridors in the southwest, and further study is needed.

## 5. Management implications

Our study found that remotely sensed NDVI data are presently not a practical means for rapidly assessing avian community species richness and abundance on the upper San Pedro River. Our NDVI models were, however, successful at predicting habitat preferences of some individual species, as Hatten and Paradzick (2003), Penhollow and Stauffer (2000), and Seoane et al. (2004) have done in other areas of the southwestern U.S. Additional investigation along other riparian systems is needed into the use of NDVI as a tool to model individual avian species of concern, namely the yellow-billed cuckoo. Our study also found that vegetation species composition and their resulting NDVI signature can be an indicator of abundance of birds, although further studies are needed to refine these relationships. While the  $R^2$  values of our models were low, we did find relationships between avian abundance and remotely-sensed variables, and if refined, these models could indicate regions of high quality avian habitat. This makes NDVI an invaluable tool to quickly assess existing riparian areas and to model sequential changes to the environment. As habitat change occurs, whether through climate change, human impacts, or habitat restoration, the ability to quickly assess and predict consequences of these changes will become critical to the conservation of these environments.

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## References

- Anderson, B.W., Laymon, S.A., 1988. Creating habitat for the yellow-billed cuckoo (*Coccyzus americanus*). technical coordinator. In: Abell, D.L. (Ed.), Proceedings of the California Riparian Systems Conference: Protection, Management, and Restoration for the 1990s. U.S. Department of Agriculture, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, pp. 468–472.
- Brand, L.A., White, G.C., Noon, B.R., 2008. Factors influencing species richness and community composition of breeding birds in a desert riparian corridor. *Condor* 110, 199–210.
- Carlisle, J.D., Skagen, S.K., Kus, B.E., van Riper III, C., Paxton, K.L., Kelly, J.F., 2009. Landbird migration in the American West: recent progress and future research directions. *Condor* 111, 211–225.
- Cersale, D.J., Guglielmo, C.G., 2010. An integrative assessment of the effects of tamarisk on stopover ecology of a long-distance migrant along the San Pedro River, Arizona. *Auk* 127, 636–646.
- Cleverly, J.R., Smith, S.D., Sala, A., Devitt, D.A., 1997. Invasive capacity of *Tamarix ramosissima* in a Mojave desert floodplain: the role of drought. *Oecologia* 111, 12–18.
- Colwell, M.A., Dodd, S.L., 1995. Waterbird communities and habitat relationships in coastal pastures of northern California. *Conservation Biology* 9, 827–834.
- Debinski, D.M., Brussard, P.F., 1994. Using biodiversity data to assess species-habitat relationships in Glacier National Park, Montana. *Ecological Applications* 4, 833–843.
- DeLay, L., Finch, D.M., Brantley, S., Fagerlund, R., Means, M.D., Kelly, J.F., 1999. Arthropods of native and exotic vegetation and their association with willow flycatchers and Wilson's warblers. technical coordinators. In: Finch, D.M., Whitney, J.C., Kelly, J.F., Loftin, S.R. (Eds.), Rio Grande Ecosystems: Linking Land, Water and People. Proceedings RMRS-P-7. USDA Forest Service, Rocky Mountain Research Station, Ogden, Utah, pp. 216–221.
- DeLoach, C.J., Carruthers, R.I., Lovich, J., Dudley, T.L., Smith, S.D., 2000. Ecological interactions in the biological control of saltcedar (*Tamarix spp.*) in the U.S.: toward a new understanding. In: Spencer, N.R. (Ed.), Proceedings of X International Symposium, pp. 819–874.
- DeSante, D.F., George, T.L., 1994. Population trends in the landbirds of western North America. *Studies in Avian Biology* 15, 173–190.
- Dockens, P.E.T., Paradzick, C.E., Hatten, J.R., 2004. Application of a southwestern willow flycatcher GIS-based habitat model: an estimate of breeding habitat in Arizona, 2001. Nongame and Endangered Wildlife Program Technical Report 223. In: Dockens, P.E.T., Paradzick, C.E. (Eds.), Mapping and Monitoring Southwestern Willow Flycatcher Breeding Habitat in Arizona: A Remote Sensing Approach. Arizona Game and Fish Department, Phoenix, pp. 28–59.
- Fody, G.M., 2005. Mapping the richness and composition of British breeding birds from coarse spatial resolution satellite sensor imagery. *International Journal of Remote Sensing* 26, 3943–3956.
- Furness, R.W., Greenwood, J.J.D., Jarvis, P.J., 1993. Can birds be used to monitor the environment? In: Furness, R.W., Greenwood, J.J.D. (Eds.), Birds as Monitors of Environmental Change. Chapman & Hall, London, pp. 1–41.
- Gaines, D., Laymon, S.A., 1984. Decline, status, and preservation of the Yellow-billed Cuckoo in California. *Western Birds* 15, 49–80.
- Gibson, L.A., Wilson, B.A., Cahill, D.M., Hill, J., 2004. Spatial prediction of rufous bristlebird habitat in a coastal heathland: a GIS-based approach. *Journal of Applied Ecology* 41, 213–223.
- Gottschalk, T.K., Huettmann, F., Ehlers, M., 2005. Thirty years of analysing and modeling avian habitat relationships using satellite imagery data: a review. *International Journal of Remote Sensing* 26, 2631–2656.
- Hatten, J.R., Paradzick, C.E., 2003. A multiscaled model of Southwestern Willow Flycatcher breeding habitat. *The Journal of Wildlife Management* 67, 774–788.
- Hatten, J.R., Sogge, M.K., 2007. Using a Remote Sensing/GIS Model to Predict Southwestern Willow Flycatcher Breeding Habitat along The Rio Grande, New Mexico. U.S. Geological Survey Open-File Report 2007–1207. <http://pubs.usgs.gov/of/2007/1207/> (accessed 1.11.08).
- Hatten, J.R., Paxton, E.H., Sogge, M.K., 2010. Modeling the dynamic habitat and breeding population of Southwestern Willow Flycatcher. *Ecological Modelling* 221, 1674–1686.
- Hughes, K.M., 1999. Yellow-billed Cuckoo (*Coccyzus americanus*). In: Poole, A., Gill, F. (Eds.), The Birds of North America. The Birds of North America, Inc., Philadelphia, Pennsylvania.
- Hunter, W.C., Anderson, B.W., Ohmart, R.D., 1987. Avian community structure changes in mature floodplain forest after extensive flooding. *Journal of Wildlife Management* 51, 495–502.
- Johnson, R.R., Haight, L.T., 1987. Endangered habitats versus endangered species: a management challenge. *Western Birds* 18, 89–96.
- Johnson, M.J., Magill, R.T., van Riper III, C., 2010. Yellow-billed cuckoo distribution and habitat associations in Arizona, 1998–1999. In: van Riper III, C., Wakeling, B.F., Sisk, T.D. (Eds.), The Colorado Plateau IV: Integrating Research and Resources Management for Effective Conservation. University of Arizona Press, Tucson, Arizona, pp. 197–212.
- Jordan, C.F., 1969. Derivation of leaf-area index from quality of light on the forest floor. *Ecology* 50, 663–666.
- Justice, C.O., Townshend, J.R.G., Holben, B.N., Tucker, C.J., 1985. Analysis of the phenology of global vegetation using meteorological satellite data. *International Journal of Remote Sensing* 6, 1271–1318.
- Knopf, F.L., Johnson, R.R., Rich, T., Samson, F.B., Szaro, R.C., 1988. Conservation of riparian ecosystems in the United States. *Wilson Bulletin* 100, 272–284.
- Laymon, S.A., Halterman, M.D., 1987. Can the western subspecies of the Yellow-billed Cuckoo be saved from extinction? *Western Birds* 18, 19–25.
- Lee, P., Ding, T., Hsu, F., Geng, S., 2004. Breeding bird species richness in Taiwan: distribution on gradients of elevation, primary productivity and urbanization. *Journal of Biogeography* 31, 307–314.
- Mathieu, R., Seddon, P., Leidecker, J., 2006. Predicting the distribution of raptors using remote sensing techniques and Geographic Information Systems: a case study with the Eastern New Zealand falcon (*Falco novaeseelandiae*). *New Zealand Journal of Zoology* 33, 73–84.
- Maurer, B.A., 1994. Geographical Population Analysis: Tools for the Analysis of Biodiversity. Blackwell Scientific Publications, Oxford.
- McGrath, L.J., van Riper III, C., Fontaine, J.J., 2009. Flower power: tree flowering phenology as a settlement cue for migrating birds. *Animal Ecology* 78, 22–30.
- Mills, G.S., Dunning Jr., J.B., Bates, J.M., 1991. The relationship between breeding bird density and vegetation volume. *The Wilson Bulletin* 103, 468–479.
- Morrison, M.L., 1986. Birds populations as indicators of environmental change. *Current Ornithology* 3, 429–451.
- Morrison, M.L., Tennant, T., Scott, T.A., 1994. Environmental auditing: laying the foundation for a comprehensive program of restoration for wildlife habitat in a riparian floodplain. *Environmental Management* 18, 939–955.
- Nagler, P.L., Glenn, E.P., Thompson, T.L., Huete, A., 2004. Leaf area index and normalized difference vegetation index as predictors of canopy characteristics and light interception by riparian species on the Lower Colorado river. *Agricultural and Forest Meteorology* 125, 1–17.
- Newbold, S., Eadie, J.M., 2004. Using species-habitat models to target conservation: a case study with breeding mallards. *Ecological Applications* 14, 1384–1393.
- Nicholson, S.E., Farrar, T.J., 1994. The influence of soil type on the relationships between NDVI, rainfall, and soil moisture in semiarid Botswana. I. NDVI response to rainfall. *Remote Sensing of the Environment* 50, 107–120.
- Nixon, P.R., Escobar, D.E., Menges, R.M., 1985. A multiband video system for quick assessment of vegetal condition and discrimination of plant species. *Remote Sensing of Environment* 17, 203–208.
- Osborne, P.E., Alonso, J.C., Bryant, R.G., 2001. Modelling landscape-scale habitat use using GIS and remote sensing: a case study with great bustards. *Journal of Applied Ecology* 38, 458–471.
- Paxton, E.H., Theimer, T.C., Sogge, M.K., 2011. Tamarisk biocontrol using tamarisk beetles: potential consequences for riparian birds in the southwestern United States. *Condor* 113, 255–265.
- Penhollow, M.E., Stauffer, F., 2000. Large-scale habitat relationships of neotropical migratory birds in Virginia. *The Journal of Wildlife Management* 64, 362–373.
- Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.-M., Tucker, C.J., Stenseth, N.C., 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology and Evolution* 20, 503–510.
- Prasad, V.K., Badarinath, K.V.S., Eaturu, A., 2008. Effect of precipitation, temperature, and topographic parameters on evergreen vegetation greenery in the Western Ghats, India. *International Journal of Climatology* 28, 1807–1819.
- Ralph, C.J., Droege, S., Sauer, J.R., 1995. Managing and monitoring birds using point counts: standards and applications. In: Ralph, C.J., Sauer, J.R., Droege, S. (Eds.), *Monitoring Bird Populations by Point Counts*, USDA Forest Service Gen. Tech. Rep. PSW-GTR-149, Albany, California, pp. 161–168.
- Rea, A.M., 1983. Once a River: Bird Life and Habitat Changes on the Middle Gila. University of Arizona Press, Tucson, Arizona.
- Robinson, T.W., 1965. Introduction, Spread and Areal Extent of Saltcedar (*Tamarix*) in the Western States. US Geological Survey Professional Paper 491-A. United States Government Printing Office, Washington, D.C.
- Seoane, J., Bustamante, J., Diaz-Delgado, R., 2004. Are existing vegetation maps adequate to predict bird distributions? *Ecological Modelling* 175, 137–149.
- Seto, K.C., Fleishman, E., Fay, J.P., Betrus, C.J., 2004. Linking spatial patterns of bird and butterfly species richness with Landsat TM derived NDVI. *International Journal of Remote Sensing* 25, 4309–4324.
- Shafroth, P.B., Stromberg, J.C., Patten, D.T., 2002. Riparian vegetation response to altered disturbance and stress regimes. *Ecological Applications* 12, 107–123.
- Skagen, S.K., Melcher, C.P., Howe, W.H., Knopf, F.L., 1998. Comparative use of riparian corridors and oases by migrating birds in southeast Arizona. *Conservation Biology* 12, 896–909.
- Sogge, M.K., Sferra, S.J., Paxton, E.H., 2008. *Tamarix* as habitat for birds: implications for riparian restoration in the southwestern United States. *Restoration Ecology* 16, 146–154.
- Steele, B.B., Bayn Jr., R.L., Val Grant, C., 1984. Environmental monitoring using populations of birds and small mammals: analyses of sampling effort. *Biological Conservation* 30, 157–172.
- Steinitz, C., Arias, H., Bassett, S., Flaxman, M., Goode, T., Maddock III, T., Mouat, D., Peiser, R., Shearer, A., 2003. Alternative Futures for Changing Landscapes: The Upper San Pedro River Basin in Arizona and Sonora. Island Press, Washington, D.C.
- Stromberg, J.C., Tellman, B., 2009. Ecology and Conservation of the San Pedro River. University of Arizona Press, Tucson, Arizona.

- Stromberg, J.C., Beauchamp, V.B., Dixon, M.D., Lite, S.J., Paradzick, C., 2007. Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid south-western United States. *Freshwater Biology* 52, 651–679.
- Strong, T.R., Bock, C.E., 1990. Bird species distribution in riparian habitats in southeastern Arizona. *The Condor* 92, 866–885.
- Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment* 8, 127–150.
- Tucker, C.J., Vanpraet, C.L., Sharman, M.J., van Ittersum, G., 1985. Satellite remote sensing of total herbaceous biomass production in the Sengalese Sahel: 1980–1984. *Remote Sensing of Environment* 17, 233–249.
- U.S. Fish and Wildlife Service (USFWS), 1995. Final rule determining endangered status for the Southwestern Willow Flycatcher. *Federal Register* 60, 10694.
- U.S. Fish and Wildlife Service (USFWS), 2000. Endangered and threatened wildlife and plants: notice of 90-day finding for a petition to list the Yellow-billed Cuckoo as endangered and commencement of a status review. *Federal Register* 65, 8104–8107.
- Van Horn, B., 1983. Density as a misleading indicator of habitat quality. *Journal of Wildlife Management* 47, 893–901.
- van Riper III, C., Paxton, K.L., O'Brien, C., Shafrroth, P.B., McGrath, L.J., 2008. Rethinking avian response to *Tamarix* on the Lower Colorado River: a threshold hypothesis. *Restoration Ecology* 16, 155–167.
- Webb, R.H., Leake, S.A., Turner, R.M., 2007. *The Ribbon of Green: Change in Riparian Vegetation in the Southwestern United States*. University of Arizona Press, Tucson, Arizona.
- Wiens, J.A., Rotenberry, J.T., 1985. Response of breeding passerine birds to rangeland alteration in a North American shrubsteppe locality. *The Journal of Applied Ecology* 22, 655–668.
- Yard, H.K., van Riper, C., Brown, B.T., Kearsley, M.J., 2004. Diets of insectivorous birds along the Colorado River in Grand Canyon, Arizona. *Condor* 106, 106–115.
- Yong, W., Finch, D.M., 2002. Stopover Ecology of Landbirds Migrating along the Middle Rio Grande in Spring and Fall. Department of Agriculture General Technical Report RMRS-GTR-99. Forest Service, Rocky Mountain Research Station, Ogden, Utah.